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SILVER DISK PYRHELIOMETRY SIMPLIFIED

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ABSTRACT

The following devices for simplifying the operation of the Abbot Silver Disk Pyrheliometer are described: (1) an automatic shutter, (2) a simplified heating and cooling timing sequence and (3) an improved method of reading the pyrheliometer thermometer. The authors also describe their experience in automatically recording the silver disk temperature by means of a thermocouple, amplifier, and recorder.

1. INTRODUCTION

The Abbot silver disk pyrheliometer is a device for measuring flux density of the direct solar beam in a plane normal to the sun's direction. Dr. C. G. Abbot, the inventor of the instrument [1], described its principle in 1908 in the following words:

> . . . In a body of measured heat capacity the rate of rise of temperature due to the absorption of radiation is noted and the loss or gain of heat to the surroundings is allowed for by cooling corrections obtained immediately before and after exposure to the sun.

The body in question here is a silver disk, blackened with an efficient absorber of solar radiation and supported in a tube designed to exclude extraneous sky radiation. The time rate of temperature change of the silver disk is determined by reading temperatures at measured time intervals by means of a mercury thermometer, the bulb of which is embedded in the silver disk.

This device is in widespread use over the world. More than 90 of them are used in various countries [2] and in many of these countries provide a basis for the standardization of solar radiation measurements.

Despite this widespread and important use, the instrument is difficult to operate. It places a very considerable burden even on the trained user, and for a beginner to acquire competence in its operation requires extensive practice. It occurred to the authors, who have lately assumed the responsibility of operating this device, that certain modifications could be made which would simplify its operation for them and possibly for others as well. The following is a report of their efforts to this end.

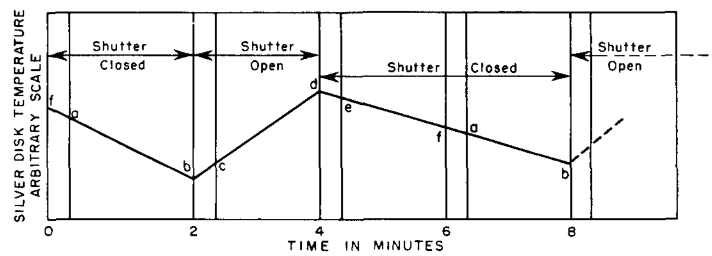
2. CONVENTIONAL PROCEDURE

A description of the procedure followed in conventional operation of the instrument appears in [3]:

> Having adjusted the instrument to point at the sun and opened the cover, read the thermometer exactly at 20 seconds after the beginning of the first minute. Read again after 100 seconds, or at the beginning of the third minute, and immediately after reading, open the shutter to expose to the sun. Note that the instrument is then correctly pointed. After 20 seconds, read again. After 100 seconds more (during which the pointing is corrected frequently), or at the beginning of the fifth minute read again and immediately close the shutter. After 20 seconds read again. After 100 seconds read again, or at the beginning of the seventh minute. Continue the readings in the above order, as long as desired. Readings should be made within 1/5 second of the prescribed time. Hold the watch directly opposite the degree to be observed, and close to the thermometer. Read the hundredths of degrees first, the degree itself

afterward . . . A special reading glass is used. It consists of a small eyepiece of about 4 cm. focal length, mounted so that it can easily be held against and moved along the thermometer stem. In the focus exactly in the center of the field is a sharp needle point. By taking readings when the needle point is opposite the top of the mercury column, parallax errors are eliminated . . . Any simple device to beat regular intervals (such as 1, 5, or 10 seconds) permits the observer to concentrate on reading the thermometer instead of trying to read both watch and thermometer at the same time. Such a device also eliminates possible error due to eccentricity of the second hand of the watch . . .

The thermometer-reading program is illustrated in figure 1. As shown, the shutter is open for 2 minutes and closed for 4 minutes.



Thermometer readings required for one observation:

Conventional procedure: a, b, c, d, e, f. (6 readings required)

Revised procedure: f, b, d, f. (The "f" reading terminating the series is the first reading of the next observation. In a series of "n" observations 3n+1 readings are required.)

Time interval between b and c, d and e, and f and a is 20 seconds.

FIGURE 1.—Shutter program and thermometer reading schedules.

3. SIMPLIFIED PROCEDURE

Simplification of the procedure was aimed at (1) automatic shutter operation, (2) simplification of thermometer reading program, (3) easing of the task of taking thermometer readings.

Automatic Shutter Operation.—Automatic shutter operation was accomplished readily. A rotary type solenoid was employed having a 67½° rotating movement. It was mounted on the barrel of the pyrheliometer and connected directly to the rotating shutter by means of a shaft. The solenoid-driven shutter is opened and closed by means of a synchronous clock switch. Time consumed in shutter movement, as determined by electronic timing equipment, is close to .01 sec.

Simplification of Thermometer Reading Program.—Examination of figure 1 shows that in conventional operation, both the heating and cooling periods are 100 seconds. (The figure represents a typical cycle, say one in the middle of a set of cycles.) The 100-second intervals do not, however, follow each other consecutively. The intervals ab, cd, and ef are separated by 20-second breaks. According to Mr. L. B. Aldrich of the Smithsonian Institution, this 20-second separation was found necessary because the inherent uncertainty in the time required for manually opening and closing the shutter would otherwise introduce errors in the timing of the periods. More reliable observations were obtained by this separation of intervals. The timing sequence is more complicated and more temperature readings are required than would be the case if the 20-second separations could be omitted. After the attachment of the automatic shutter, the 20-second intervals were no longer necessary, hence the time interval sequence or complete cycle for an observation was chosen to consist of three 2-minute periods, one immediately after the other. This sequence results in three fewer temperature readings during a complete observation and a simpler and easier-to-follow timing schedule. Comparisons of results obtained using the old and new timing cycles revealed no significant difference in the calculated flux density for a given period (actually one part in a thousand, in the mean of one set of 9 pairs of readings).

Easing the Task of Reading the Thermometer.—The thermometer on the silver disk pyrheliometer is scaled in the Celsius system, the smallest scale division being 0.1° C. In use, the temperature is estimated to tenths of a division, or .01° C. To facilitate this reading, a low-powered reading glass is held above the mercury column as described in the conventional procedure [3]. The ease of using this glass has been increased by mounting it on a spiral-threaded shaft which is rotated by a crank at the end of the shaft. The shaft is mounted parallel to the thermometer. The pointer of the reading glass can easily be maintained on the end of the mercury column as it rises or falls, by rotating the crank. A buzzer system gives a 10-second warning interval during which the buzzer sounds continuously—at the end of which cranking is stopped. The position of the top of the mercury column as located by the now stationary pointer can be read at leisure, relatively speaking.

Since the heating and cooling periods are equal, each of a 120-second duration, the timing buzzer is made to sound for the last 10 seconds of each 2-minute period. In practice, by means of a synchronous clock switch, the buzzer is automatically synchronized with the pyrheliometer shutter and also with a large-dial clock equipped with sweep second and minute hands. The minute divisions of the clock, in addition to being numbered, are differentially colored, 2 red and 4 white, consecutively around the dial. The synchronization is so arranged that when the minute hand is over the red markings, the shutter is open, when over the white it is closed. It is thus possible to keep track visually of the progress of the timing sequences. A complete observation starts 2 minutes before the shutter opens and ends 2 minutes after the shutter closes. A glance at the dial at any time during any observation is sufficient to determine just how long it will be before the shutter opens or closes as the case may be.

The use of a motor-driven polar mounting is planned to ease the chore of keeping the pyrheliometer pointed continuously at the sun.

Automatic Temperature Recorder.—When the authors first considered the problem of simplifying the operation of

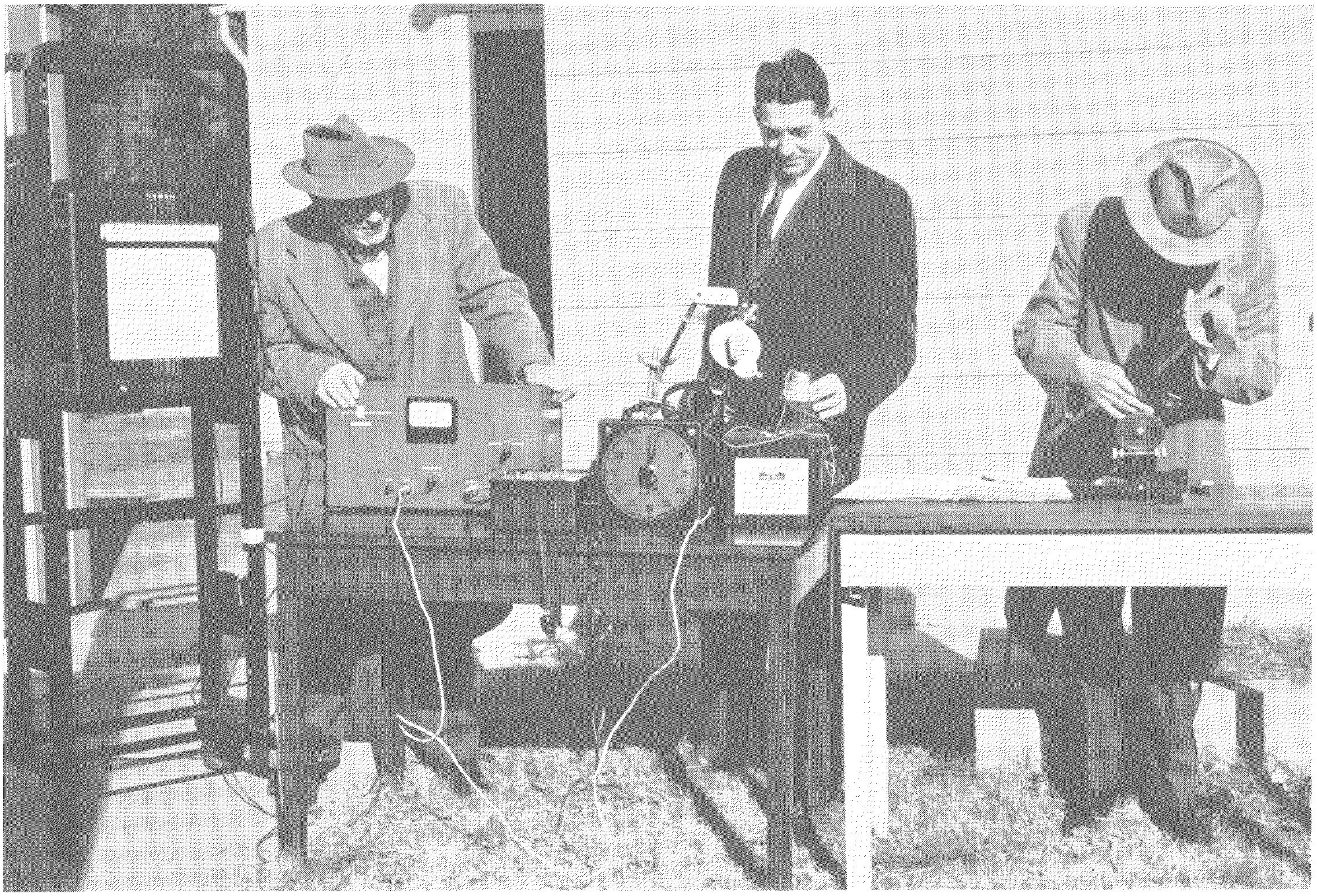


FIGURE 2.—Preparation of normal incidence solar radiation equipment for operation at the Smithsonian Institution. (Left to right, Norman B. Foster, T. H. MacDonald, and L. B. Aldrich.)

the silver disk pyrheliometer they enthusiastically contemplated the use of a thermocouple and recorder for automatically recording the temperature of the silver disk, thus eliminating completely the task of reading the thermometer.

This modification was made and used successfully. After some experience, however, there arose a serious question as to whether the use of automatic temperature recording is a step in the direction of simplification.

The modification consisted of embedding a single-junction copper-constantan thermocouple in the silver disk close to the thermometer bulb. The output of the couple was fed into a breaker-type d-c amplifier and the amplifier in turn fed into a strip-chart potentiometer-recorder. Figure 2 shows the apparatus ready for use.

An analysis of the data obtained with this recording system suggested that the accuracy obtained may have been slightly better on individual observations than those obtained by using the eye-read thermometer. For the average of a set of readings, comprising four or five or more observations, differences between the recorder and conventional results were insignificant. There is some advantage in having the trace as a record which can be checked, whereas the eye-read thermometer reading cannot be checked once made. However, the care in setting up the amplifier-recorder apparatus, in our case out-of-doors, and the necessity for a painstaking calibration of the system, have convinced the authors that the amplifier-recorder system as they employed it presents too many disadvantages to justify its use as a standard procedure.

A complete description and discussion of the amplifier-recorder equipment is given in the Appendix.

4. CONCLUSIONS

Observations with the silver disk pyrheliometer are substantially simplified by the use of auxiliary devices and revised procedures described above. The use of a thermocouple in conjunction with an amplifier-recorder unit for measuring the temperature of the silver disk is believed not to possess sufficient advantage to justify its use as standard procedure.

A statement giving data on calibration of the Weather Bureau silver disk pyrheliometer will be published after more data are obtained.

APPENDIX

A schematic diagram of the equipment used for automatic temperature recording of the silver disk temperature is shown in figure 3. A small hole was drilled in the silver disk and a single-junction copper-constantan thermocouple was embedded in the disk close to the thermometer. A thermos bottle filled with ice and water contained the thermocouple cold junction. The thermocouple was connected to a breaker-type d-c amplifier having an amplifier factor of about 20X. The output of the amplifier was connected to a strip-chart potentiometer-recorder using a paper feed of 4 inches per minute.

If the amplifier-recorder circuit is arranged to record the actual value of temperature on the Celsius scale, then the variations in the temperature—which are the most important element in computation of flux density—are not given in fine enough detail to give the accuracy needed. To overcome this difficulty, the circuits were arranged so that the variations, usually amounting to 2° or 3° C. for any one complete cycle or reading, occupied substantially the complete recorder range. This was done by "elevating the zero" as shown in the circuit schematic.

A voltage sufficient to position the pen near the bottom of the record at the beginning of the observations, when the silver disk is cold, was connected in the circuit by means of a potentiometer in opposition to the voltage generated by the thermocouple. (The corresponding temperature was also read from the silver disk thermometer.) Ideally, a calibrating voltage should be injected into the amplifier immediately before and after the series of observations is made.

Calibration of the Amplifier-Recorder Unit.—Calibration of the amplifier-recorder unit is a vital matter in accuracy control. The circuit used in calibration is shown in figure 3.

A pre-selected current, I, measured by the milliammeter, is sent through the precision resistor R. The voltage drop across the calibrated resistor is then fed to the amplifier and thence to the recorder.

Full scale on the recorder at the recorder input terminals is 6 millivolts.

Corresponding full-scale input to the amplifier, which has a nominal amplification of 20, is close to $6(10^{-3})/20$ or 3×10^{-4} volts.

Resistance of the calibrated resistor R is .01 ohms within $\pm$.02 percent.

Full scale current I through R is then 3×10^{-2} amperes.

Calibration voltage requires that the error be no greater than 0.5×10^{-6} volts. This corresponds to an error of .01° C. in the indicated temperature.

Accuracy of the milliammeter, 0.3 percent; full-scale 10 milliamperes.

Amplification factor "a" is nominally 20.

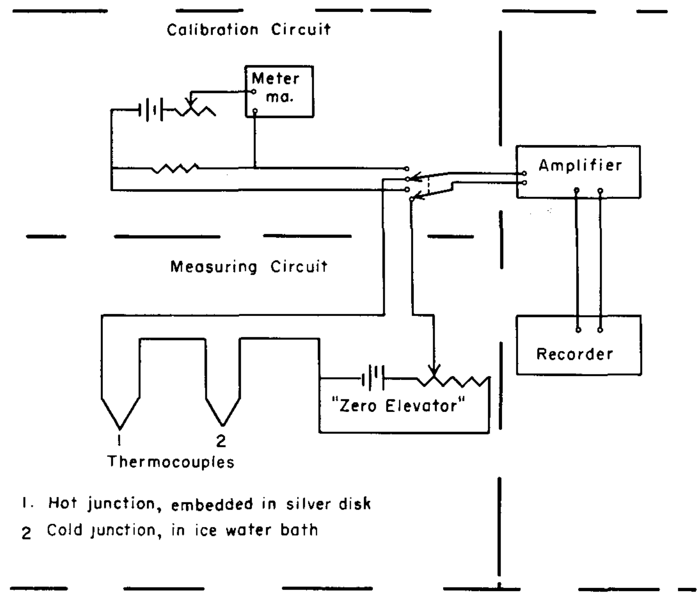


FIGURE 3.—Equipment for automatic recording of silver disk temperature. A more refined apparatus is described in [5].

From $E=IR$ one obtains

$$\Delta E=I\Delta R+R\Delta I$$

Here $R=10^{-2}$ ohms, $\Delta R=2(10^{-6})$ ohms

$I=10^{-2}$ amperes, $\Delta I=3(10^{-5})$ amperes

$\Delta E=10^{-2}[2(10^{-6})]+10^{-2}[3(10^{-5})]=0.32(10^{-6})$ volts

$\simeq$0.3 microvolts

This corresponds to a temperature error of a little less than .01° C.

The calibrating voltage developed by 10 milliamperes across the .01 ohm resistor would give a recorded deflection of about ⅓ of full scale. The reading error of the recorder is about 0.1 percent of full scale corresponding to about ⅓ microvolt. The combination of errors of calibrating voltage (0.3 microvolt) and the reading error (0.3 microvolt) would lead to an error of less than .02° C.

For converting signal to temperature, the authors obtained data on the correspondence of voltage generated by the copper-constantan thermocouple to temperature, to four significant figures, from the National Bureau of Standards [4]. A second-degree equation was computed which fits the data in all cases to the four places given. The data were for 1° C. increments. The parameters in the equation were computed to a sufficient number of places to permit use of the equation in interpolation of the voltages to .01° C. The comparison of results to be described indicates that this procedure did not introduce any systematic error.

Details of Results of Observations.—On September 2, 1954, the weather was favorable for making normal incidence measurements. The equipment was taken to the Smithsonian Institution and set up there for calibration of our modified normal incidence silver disk pyrheliometer S. I. No. 78 against the Smithsonian APO No. 8 bis.

Three sets of data were obtained. One set was taken using the conventional procedure. The next set was obtained by using the same set of original thermometric readings as in the first case, but omitting readings c, e, and a. The third set was obtained using the amplifier-recorder equipment. Calibration of this unit was done later in the laboratory and not as would be the ideal procedure—immediately before and after the set of observations at the Smithsonian Institution. Nevertheless, results of the calibration give an agreement between the recorder results and mercury thermometer computations within about 0.1 percent.

Because use of the recorder was not contemplated in practice, no further comparisons were made.

ACKNOWLEDGMENT

The authors are indebted to Mr. L. B. Aldrich for making available technical assistance for the installation of the thermocouple in the silver disk pyrheliometer and for supplying solar radiation flux density values for the calibration of the modified equipment.

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CORRECTION

MONTHLY WEATHER REVIEW, vol. 83, No. 1, p. 6: Cuts for figures 9 and 10 are reversed. The one on the right should be figure 9, the one on the left, figure 10.